

Research on the peak of CO₂ emissions in the developing world: Current progress and future prospect

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HIGHLIGHTS

- Timeline to peak CO₂ emissions remains hard to determine for the developing world.
- China has a great chance to reach an earlier peak of CO₂ emissions before 2030.
- Peaking CO₂ emissions by 2040 will be too high to pay for India and hardly to realize.
- A rapid transition of major developing nations into low-carbon sustainable pathways.
- Four topics urgently require further study in the future.

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ABSTRACT

The developing world will largely determine the trajectory of future global CO₂ emissions. An accurate projection of CO₂ emissions from the developing world and a good understanding of possible timelines and pathways to reach their peaks are of great significance to combat global climate change. This issue has recently attracted increasing attention; however, it is far from solved. China and India are the two largest developing countries and have a decisive influence on CO₂ emissions growth across the developing world. This article critically reviews the current literature regarding CO₂ emissions projections of the developing world, particularly of China and India, with an aim to summarize recent study progresses and enlighten future studies. It is generally agreed that China will peak its CO₂ emissions by 2030 and has an excellent chance of reaching an earlier peak during 2020–2030. By contrast, India is very likely to undergo sustained emissions growths for decades. The constraints of keeping global warming below 2 °C may enable India to peak CO₂ emissions by 2040; however, the associated costs will be too high to pay. Across the developing world, the timeline to peak CO₂ emission remains difficult to determine; however, a rapid transition of major developing countries towards low-carbon sustainable development is essential for reaching such a peak. Four topics urgently require further study in the future: improvements in study methodology and data, key country groups and fields to peak CO₂ emissions, the peak morphology and post-peak CO₂ emissions in China, and a more in-depth understanding of the timeline and pathway to peak CO₂ emissions in India.

1. Introduction

The significant growth of anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era is extremely likely to be the dominant cause of recent abnormal changes in global climate system [1]. If no action is taken, continuous GHG emissions¹ and the resultant long-lasting climate change will pose a risk of severe, pervasive and

irreversible impacts on humanity and ecosystems [1]. To keep global average warming below 2 °C relative to pre-industrial levels, anthropogenic carbon emissions must be totally offset by carbon sinks in the second half of this century [2,3], an achievement of which needs urgent and concerted efforts from countries at all levels of development [4,5].

Developing countries are playing an increasingly important role in global climate change mitigation. Although developed countries

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¹ There are six types of main GHG, including CO₂, CH₄, N₂O, HFCs, PFCs and SF₆. CO₂ emissions is one of the most important human-induced GHG emissions, contributing nearly 80% of the total GHG emissions growth from 1970 to 2010 [1]. In this study, we mainly focus on CO₂ emissions and call it as carbon emissions.

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Nomenclature

BAU	Business-as-Usual
BRICS	Brazil, Russia, India, China, and South Africa
BU	Bottom-up
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium
COP21	The 21st Conference of the Parties
EKC	Environment Kuznets Curve

ETS	Emissions Trading Scheme
GDP	Gross Domestic Product
GHG	Anthropogenic Greenhouse Gas
IAM	Integrated Assessment Modelling
INDCs	Intended Nationally Determined Contributions
MAC	Marginal Abatement Cost
TD	Top-down
UNFCCC	United Nations Framework Convention on Climate Change

contribute more to global historical cumulative emissions, developing countries show a faster rate of CO₂ emissions growth in recent decades and account for a rising share of the world's total emissions annually [6,7]. As presented in Fig. 1(a) and (b), the amount of CO₂ emissions from developing countries surpassed those from developed countries in 2005 and currently constitutes 63.4% of global total emissions. Moreover, in contrast to absolute emissions reductions in the developed world, CO₂ emissions from the developing world grew by 6753.2 Mt during 2006–2016 and are expected to continue growing in the foreseeable future [8,9]. Consequently, the developing world has become a dominant driver of global emissions growths and will largely determine the trajectory of global emissions throughout this century [9,10]. Therefore, an accurate projection of CO₂ emissions from the developing world is of great importance for formulating scientifically effective strategies to combat global climate change [11,12]. This topic has recently received increasing attention. However, fierce controversies and high uncertainties are still widespread due to remarkable differences in the stage of development, the tendency of CO₂ emissions, and the ambition of emissions mitigation across various developing countries, as well as their long-standing reluctance to engage in regular CO₂ emissions stocktaking and data transparency.

China and India are the two largest developing countries from both the economic and demographic perspectives and are the largest developing-world CO₂ emitters. As illustrated by Fig. 1(c), China and India accounted for 44.2% and 10.6%, respectively, of the total CO₂ emissions of the developing world in 2016. Over the past decade, they have collectively contributed 70.5% of increased emissions in the developing world and 83.7% of increased emissions worldwide [8].

Moreover, because of differences in development stages, these two countries put forward two different types of emissions reduction pledges. China, with a relatively high development level of industrialization and urbanization, has made an official commitment to peak its CO₂ emissions by 2030 and strive to reach the peak as early as possible [13]. India, which suffers from severe electricity shortages and has very low CO₂ emissions *per capita*, has no explicit target for controlling its absolute emissions but has committed itself to cutting emissions per unit of gross domestic product (GDP) by 33–35% by 2030 [14]. Considering the large scale of emissions and the typicality of emissions mitigation commitment, China and India have important implications for obtaining a better grasp of the growth and peak of CO₂ emissions in the developing world.

Given the great importance of the developing world in combating global climate change, this article provides a critical review of the current studies on CO₂ emissions projections of developing countries and particularly of the two representative countries of China and India. It aims to contribute to the literature in three ways: by providing a clear picture of the present study status and progress, by making a systematic evaluation of the present study findings, consensus and their policy implications, and by offering insights into the urgent problems that require further study. By doing these works, the study can to some extent bridge the gap in the current literature which lacks a systematic commentary on CO₂ emissions tendency in the developing world, while also providing readers with two typical case descriptions to better understand emissions trends across developing countries at different stages of development.

The rest of this article is organized as follows. Section 2 takes

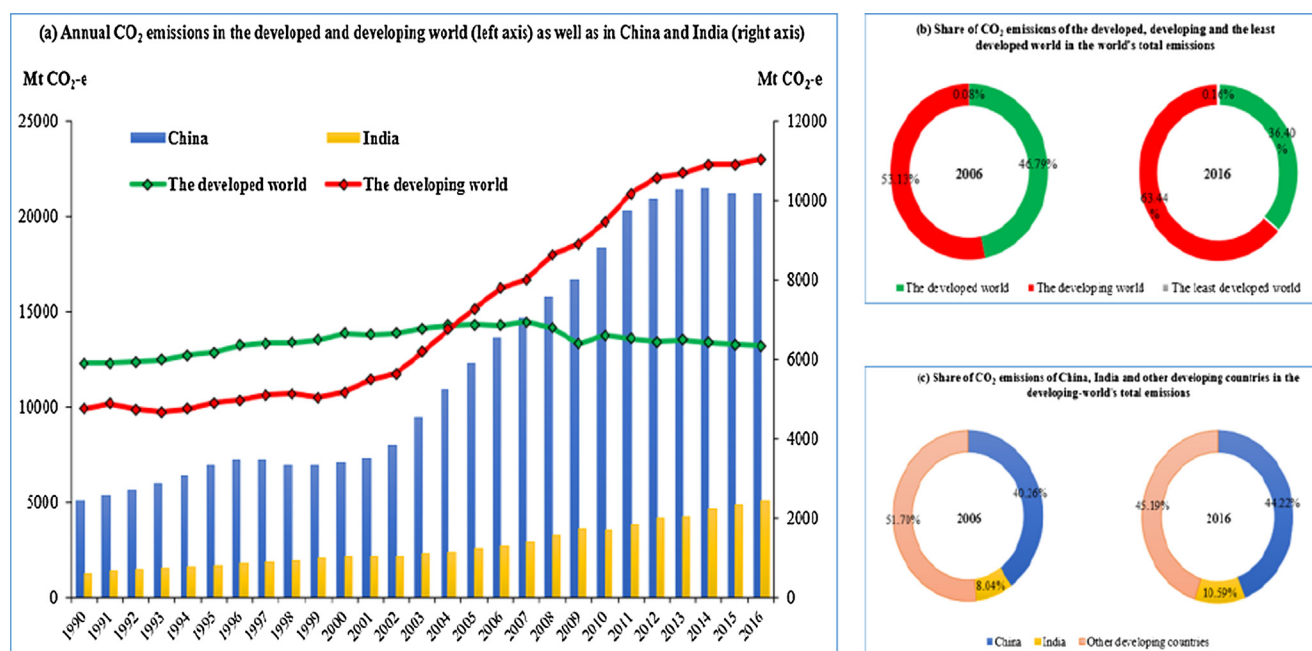


Fig. 1. The dynamics and the share of CO₂ emissions in the developed and developing world as well as in China and India.

developing countries as a whole to review the recent literature on CO₂ emissions projection of the developing world, while Section 3 and Section 4 pay close attention to the growth trend and the peak of CO₂ emissions in China and India, respectively. Based on this information, Section 5 summarizes the current research findings and consensuses and discusses their policy implications for controlling CO₂ emissions from developing countries. Finally, Section 6 identifies highly controversial or uncertain issues and provides insights into certain key topics that urgently require further research. The framework of the article is illustrated in Fig. 2.

2. Research on CO₂ emissions projection of the developing world

Carbon emissions from the developing world attract increasing attention because of their increasing quantity and expected continuous growth in the coming decades. The section discusses the recent literature on CO₂ emissions projections of the developing world from two major perspectives: estimating the possible trajectories of future CO₂ emissions and discussing how the recently issued Intended Nationally Determined Contributions (INDCs) and the global 2 °C target affect future emissions, as illustrated in Table 1.

2.1. Future trajectory of CO₂ emissions in the developing world

A variety of econometric and numerical simulation studies have been conducted to project future CO₂ emissions in the developing world, which approach this question from different angles, based on different scenario hypotheses, and yield different results.

The Environment Kuznets Curve (EKC) hypothesis provides an important tool to analyse how CO₂ emissions dynamically evolve with economic development. Several studies showed that the elasticity of CO₂ emissions relative to economic growth was significantly positive and tended to decline with rising incomes in many developing countries [15,16]. It was implied that the developing world might continuously emit massive amounts of CO₂ in the near future until they reach a considerably high level of income. Other studies further made a cross-

national analysis of the EKC hypothesis on CO₂ emissions. Empirical results also indicated continuous growths of CO₂ emissions from the developing world in the near future [17]; however, the applicability of the EKC hypothesis varied greatly across countries with different characteristics and at different development stages [18,19]. The large emitters and the developing countries that were about to enter high-income levels needed to pay special attention to their low-carbon consumption transition. Moreover, the year-by-year decoupling state of CO₂ emissions from economic growth was discussed for developing countries. Relative to developed countries that had already entered or had high potentials of reaching absolute decoupling, most developing countries still fluctuated in an interval of relative decoupling due to their weak technical progress and structural updating effects. Hence, CO₂ emissions in the developing world were expected to keep growing and contribute the most to increased emissions worldwide [20]. On the other hand, specific decoupling states differed substantially by country. The effect of economic activity contributed to the continual growth in CO₂ emissions in China and India while offsetting them in Russia, Brazil, and South Africa, resulting in significantly different trends of emissions growth across developing countries [21].

In addition, some studies discussed the major factors affecting carbon emissions and estimated their potential impacts on future emissions. Expanding production and consumption activities tended to raise CO₂ emissions across the developing world [22]; however, the effects on individual developing countries were quite mixed and must be examined on a case-by-case basis [23]. Additionally, a positive elasticity of CO₂ emissions relative to urbanization was found in many developing countries, indicating that an ongoing urbanization process would drive up emissions in the developing world in the next several decades [24,25]. Moreover, the dominant driving forces of emissions growth varied significantly by country groups [26]. For the coming decade, a large increase of CO₂ emissions was expected for low-income developing countries, behind which a rapidly expanding production activity would constitute the top contributor, followed by rising urbanization [27].

Furthermore, globalization and international trade allows countries

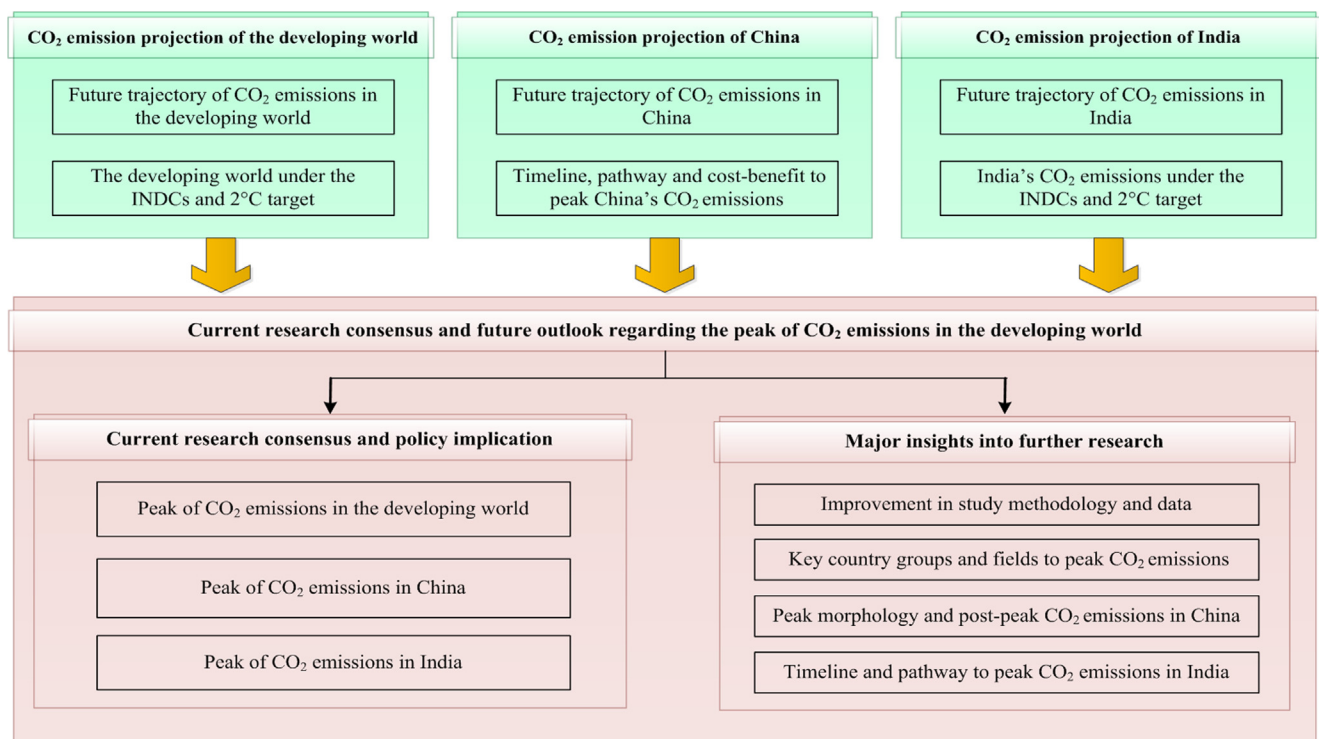


Fig. 2. The overall framework of this article.

Table 1
Research on CO₂ emissions projection of the developing world under two broad categories.

Research category	Major research finding	Reference
Future trajectory of CO ₂ emissions in the developing world	The developing world will continuously emit a massive amount of CO ₂ emissions in the near term until major developing countries attain high enough income levels and transform into green development pathways	[15,16,18–20]
	Expanding economic activities, industrialization and urbanization will largely drive CO ₂ emission growth in the developing world over the next few decades. The growing international trade and production outsourcing tend to cause large-scale CO ₂ emission transfers from the developed to the developing world and eventually may pose net effects on raising global emissions	[24,25,27–30,45–47,49,50]
	The applicability of the EKC hypothesis, the degree of decoupling, and the growing trend of CO ₂ emissions vary greatly across developing countries with different characteristics and at different development stages	[21–23,27]
	The populous emerging economies and the industrial and infrastructure sectors are expected to constitute the main parts of future CO ₂ emission growths in the developing world	[38,43,44]
The developing world under the INDCs and 2 °C target	The newly submitted INDCs, if fully implemented, will greatly alleviate CO ₂ emissions; however, they will still be unable to stop emissions from growing until 2040 in many developing countries. Consequently, the developing world will continue to face large gaps in enabling CO ₂ emissions abatements to meet the global 2 °C target	[62,63]
	The current practice of many developing countries can hardly enable full fulfilment of their INDCs, making the expected emission reduction effects of the developing world less ambitious and more uncertain	[64,65,67–69]
	To realise the global 2 °C climate target requires the developing world to ramp up emission mitigation ambitions and to make ongoing efforts on establishing green energy systems, improving energy efficiencies across all end-use sectors, pursuing a low-carbon process of industrialization and urbanization as well as shifting towards sustainable lifestyles and development pathways	[75–78,80–82,88,91–94]

to increasingly rely on the production activities of foreign countries to satisfy their domestic demands, which spark heated debate on trade-induced CO₂ emissions transfer and consumption-based emissions accounting. Nasreen and Anwar [28], Ahmed et al. [29], and Behera and Dash [30] found that trade openness tended to drive up energy consumption and CO₂ emissions in Asian countries over the long term. Moreau and Vuille [31] and Wiedmann and Lenzen [32] were aware that when considering emissions embodied in trade, the decarbonized progress of most developed countries was not so optimistic as previously believed, and the production-based CO₂ emissions were often higher than consumption-based emissions in developing countries. Fernández-Amador et al. [33] performed a comparative analysis showing that income-driven growth in consumption-based CO₂ emissions tended to be more intense than that associated with production in most surveyed countries. They also expected a rising level of CO₂ emissions embodied in global supply chains and final consumption with future rising incomes. For fairness, the consumption- or footprint-based accounting of CO₂ emissions has been increasingly proposed [34]. Additionally, Jakob and Marschinski [35] not only detected the net transfer of CO₂ emissions from developed industrialized countries to their trading partners but also noticed that this trade-induced transfer potentially increased global emissions. Wei et al. [36] further explored how carbon transfers might affect the global climate, discovering that a continuous growth of carbon transfers from developed to developing countries had exerted a climatic effect on raising global atmospheric CO₂ concentrations. Thus, the trade-induced transfer of CO₂ emissions and its impact on developing-world and global emissions, as well as the alternative approaches of CO₂ emissions accounting, require more attention in international climate negotiations.

In addition to the above researches, other scholars applied energy planning, input-output, computable general equilibrium (CGE), or integrated assessment modelling (IAM) models to simulate future CO₂ emissions. Energy consumption and its structure would have large impacts on future CO₂ emissions from developing countries [37]. Given the uneven distribution of energy services between developed and developing worlds, populous emerging economies were expected to constitute a main component of future global emissions growth [38]. Although a decline in energy demand would be hardly achievable for the developing world until 2050, maintaining a minimum growth in energy consumption and simultaneously decreasing carbon intensity of energy

could largely alleviate emissions growth [39]. Moreover, there remained large gaps regarding the application of current energy planning models to a developing-world context due to the poor quality of data, inadequate consideration of socioeconomic nuances [40,41], and high uncertainty in economic and industrial development [42]. Energy-related CO₂ projections of developing countries, hence, should make additional efforts to account for structural change, socioeconomic feedback and suppressed energy demand.

Furthermore, the economy-wide modelling studies were carried out by [43,44], estimating that CO₂ emissions from industrial sectors and infrastructure building would grow most rapidly in the developing world. Hence, developing countries should seek more environment-friendly ways to realize industrialization and construct infrastructure systems. The impact of international trade on CO₂ emissions also garnered increasing attention in numerical simulation studies. Arto and Dietzenbacher [45] and Vries and Ferrarini [46] found that although the growth of CO₂ emissions in emerging countries accounted for the majority of global overall growth, a substantial share of their growth was caused by increased participation in global supply chains and changes in advanced countries. Liddle [47] and Fan et al. [48] made a multiple-dimension comparison of production-based and consumption-based CO₂ emissions. Their main results indicated that consumption-based emissions *per capita* grew more prominently than production-based emissions with rising incomes, and the differences between them significantly varied by country. Zhang et al. [49] further revealed that in a new context of the service-oriented economy, rising service demands and final consumption in certain developed countries was the main driver of increased CO₂ emissions in other countries.

Additionally, trading and linkages among developing countries have also been significantly strengthening in recent years, which has exerted important influences on both developing-world and global CO₂ emissions [50]. Cai et al. [51] made an empirical investigation of the Belt and Road, finding CO₂ transfers both from developed countries to China and from China to less-developed countries. Arce et al. [52] and Shahbaz et al. [53] examined how the new upsurge of the Post-China 16 and Next-11 countries² in global production chains affected future

² The Post-China 16 countries include Ethiopia, Kenya, Tanzania, Uganda, Dominican Republic, Mexico, Nicaragua, Peru, Cambodia, Indonesia, Laos, Myanmar, Philippines, Vietnam, Bangladesh, Sri Lanka. The Next-11 countries

emissions pathways, respectively. According to their analyses, the new trade replacements had a potential of cutting global CO₂ emissions, but the final outcomes depended on whether host countries and enterprises relocated their productions to environmentally efficient countries. The rising South-South trade was also an emerging trend. Kim et al. [54] revealed that trading between developing countries and the global South contributed to mitigating CO₂ emissions in developing countries but might worsen emissions in their partner countries, particularly in the more polluted ones. Meng et al. [55] not only detected an increasing emissions transfer towards less developed countries (e.g., Vietnam and Bangladesh) but also pointed out that such a redistribution of emissions throughout the global South might undermine global climate efforts. Overall, either the trades between developed and developing countries or those among different developing countries might cause extra emissions in the developing world, which required more attention in future [56,57].

2.2. The developing world under the INDCs and 2 °C target

It has been widely agreed that CO₂ emissions of the developing world will continue to grow for the next few decades or even through to the middle of the century. However, to obtain a decent chance of avoiding the most catastrophic climate change, we must limit global warming well below 2 °C relative to the pre-industrial levels³ and achieve a 40%–70% reduction in global anthropogenic CO₂ emissions by 2050 relative to 2010 [1]. Hence, although the developed world has begun a declining trend of emissions, slowing down and then stopping CO₂ emissions growth in the developing world is indispensable and urgent [61].

At the 21st Conference of the Parties (COP21), the member countries under the United Nations Framework Convention on Climate Change (UNFCCC) were asked to submit their INDCs⁴, and by which, they should outline their post-2020 climate actions to contribute to a 2 °C global target. The newly submitted INDCs would fulfil a critical role in determining future CO₂ emissions from the developing world. Compared with the current trajectories, INDCs submitted by both developed and developing countries would contribute to largely enhanced reductions in global CO₂ emissions but still face large gaps in meeting global climate targets for both 2025 and 2030 [62,63]. To narrow these gaps, countries at all levels of development should assume the full implementation of their INDCs and, more importantly, the developing world should ramp up climate ambitions and make a rapid transition towards decarbonization.

To take a closer look at developing emitters, climate policies committed by INDCs were projected to greatly alleviate CO₂ emissions; however, they are still unable to stop emissions from growing until 2040 in most developing countries [63]. What is worse, the current practice of many developing countries can hardly meet the commitments in their INDCs, resulting in great uncertainties in INDC outcomes [64,65]. Moreover, we should be aware that not all targets pledged by developing countries were unconditional to be reached by their efforts alone. In fact, many countries tended to set conditional targets that would rely on external assistance [66]. According to the simulation

results, achieving conditional targets could promote further CO₂ emission reductions on a basis of unconditional targets [67]. However, the associated costs would be too high for most developing countries and hence require large-scale assistance from developed countries [68,69]. Consequently, conditional climate targets and their reliance on international resources make the expected effects of INDCs less ambitious and more uncertain. For instance, simulation analyses for Brazil showed that the achievement of national INDCs would increasingly rely on energy system [70], while the high uncertainties in energy demand, penetration of renewable energy, market barrier [71] and in potential of carbon capture and storage (CCS) [72] posed the major challenges. For South Africa, it was reported that a transition towards green energy and economy could largely reduce CO₂ emissions and enable more resilient growth in the long run, but such a transition faced significant uncertainties in terms of political and institutional stability, energy strategy, infrastructure building, technical skill and funding source [73,74].

As is clear from the above discussions, the situation of CO₂ emissions outlined by the INDCs remains far from optimistic for the developing world. Against this, some studies applied back-casting analyses to explore the possible pathways for realizing the 2 °C target [75,76]. The great importance of a rapid transition to low-carbon sustainable development was addressed [77]. First, developing countries, particularly emerging economies, must build green energy systems to feed swiftly growing energy demands [78]. Taking the BRICS (Brazil, Russia, India, China, and South Africa) countries as an example, increasing natural gas and renewable energy consumption could abate CO₂ emissions substantially and helped achieve the peak of emissions at lower levels [79]. In Asia, the deployment of renewable energy sources must be continually increased in the energy mix until fossil fuels were largely replaced, which would contribute to the largest part of regional CO₂ emission reductions by 2050 [80,81]. For a broader range of developing countries, raising the share of renewable energy consumption was also verified as a critical precondition for realizing low-carbon economic growth [82]. To unleash the potential of renewable energy in CO₂ emissions reduction, developing and emerging countries in the global South not only needed strong domestic institutional and policy supports but also must rely on international assistance from their colonial peers and the European Union [83]. It should also be noted that some relatively advanced developing countries, e.g., China, India and the BRICS countries, have begun to play increasing roles in renewable energy investment and technical transfer towards more underdeveloped countries, e.g., Sub-Saharan Africa [84]. Moreover, the policy and process to promote renewable energy development should be specific to each country and reconciled with national realities [85]. The establishment of smart and polycentric power grids has also been a challenge. Country-specific pilot projects of smart grids and dispatching learning were, thus, strongly suggested for the developing world [86,87].

Second, improvements in energy efficiency across all end-use sectors would fulfil a critical role in suppressing energy demand growth [88]. The average energy efficiency level of developing countries presented a large gap to the international advanced level [89]. Improving energy efficiency was thus widely recognized as a critical strategy for developed countries to tackle energy security and climate challenges, particularly in the current economic recovery stage [90]. The effect of energy efficiency measures varied by the sectors where energy savings occurred and was also related to regional industrial feature, energy consumption structure and power generation mix, all of which needed careful considerations to better exploit their potentials [91]. Moreover, the cost of most energy efficiency measures could be totally offset by subsequent energy saving benefits. It was implied that improvement in energy efficiency could achieve most of its effects at zero or negative costs, providing the developing world one of the most cost-effective means of emission reduction [92]. Hence, energy efficiency measures would be the easiest to implement in the developing world in near

(footnote continued)

include Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, Turkey, South Korea and Vietnam.

³ Some studies argued that the limit of the global 2 °C warming would be not enough to avoid the most disastrous consequences of climate change and urged more stringent targets to limit global temperature rise below 1.5 °C or even 1 °C relative to pre-industrial levels [58–60]. Under these cases, human society must conduct more immediate and more ambitious reductions of carbon emissions.

⁴ INDCs are voluntarily submitted by the member countries. However, they will become firm commitments and be called as NDCs once the Paris Agreement is ratified and comes into effect. For the sake of convenience, we consistently use the INDCs throughout the article.

terms, particularly before 2030.

Last but not the least, shifting towards a low-carbon sustainable growth pathway was warranted for the developing world to satisfy its growing socioeconomic demands with the least CO₂ emissions [93]. The past decade has seen fundamental changes in technology, economy and urbanization around the world. Rebuilding of socioeconomic development scenario would have important implications on future CO₂ emissions projections. According to multi-model simulations, the long-term emissions trajectory and the carbon pricing and associated costs to reach the 2 °C target would illustrate widespread uncertainties across socioeconomic narratives and policy assumptions [94]. Technological progress and innovation have been fundamental conditions to decouple CO₂ emissions from economic growth. It was reported by both the fifth assessment report of the IPCC [1] and Jones et al. [95] that, most scenarios limiting global warming to 2 °C would require not only decarbonization technologies but also negative emissions technologies in the second half of this century. Although the newly proposed negative emissions technologies theoretically had big potentials to promote climate stabilization, their enforceability [96] and credibility [97] remained highly unclear in practice. In addition, they have also been criticized as a risky strategy that might cause a dangerous lock in carbon addiction [98] and an unjust gamble for future generations [99]. Based on this information, the widespread diffusion and application of decarbonization technologies remain a top priority for current emissions reduction. Meanwhile, further exploration into the real effect of negative emissions technologies is also sorely needed.

Moreover, as many developing countries have chosen industrialization as their primary development strategy, climate concerns should be increasingly integrated into national industrial objectives to encompass a decarbonized process of industrialization [43]. The adjustment of industrial structure to green production showed good potentials in cutting CO₂ emissions, but its realization needed policy incentives for green industry, system innovation across multiple fields, and effective management of uncertainty and risk across long-time horizons [100]. Global production and supply chains and their shifts also affected CO₂ emissions in the developing world. An empirical analysis showed that from 1995 to 2009, domestic CO₂ emissions of developing countries such as China and Russia increased for global production fragmentation, whereas those in developed countries such as Germany and Japan decreased [101]. On the other hand, a shift in global supply chains from China and India to their successor countries,

such as South Asia, Africa and Latin America, recently emerged, causing net carbon transfers to the global South [55]. Driven by the indirect effects associated with rising consumption and infrastructure in successor countries, such a shift might lead to growth in global total emissions and thus awaited serious attention to low-carbon technology transfers with trade [102]. Additionally, with the industrialized process and the increased participation in global supply chains, income levels and in turn domestic consumptions largely increased in developing countries, constituting a primary driver of growths in their territorial CO₂ emissions [46]. Hence, even for developing countries, it was equally important to prevent the increases in consumption-induced emissions *per capita* with rising incomes. Pursuing a sustainable development of urbanization [103,104] and promoting the formation of low-carbon consumption patterns and lifestyles [105,106] would play increasingly important roles in controlling CO₂ emissions in the developing world, particularly in populous developing economies.

3. Research on CO₂ emissions projection of China

China is the largest developing country and the top CO₂ emitter in the developing world. Moreover, the country has officially committed to actively responding to climate change and reaching a peak of CO₂ emissions by 2030. Whether China can effectively control its CO₂ emissions, therefore, is of major significance in understanding the trends of future developing-world emissions. According to the national emissions reduction commitment and different study emphases, the literature on China's CO₂ emissions projections can be classified into two broad categories. The first category estimates the trend of CO₂ emissions in China and attempts to testify the existence of an emissions peak by 2030; by contrast, the second category of study assumes the existence of CO₂ emissions peak as a prerequisite and focuses on the timeline, pathway and cost-benefit to reach this peak, as shown in Table 2.

3.1. Future trajectory of CO₂ emissions in China

The current literature has applied a variety of methods and models to estimate the possible trajectory of CO₂ emissions in China, as illustrated in Fig. 3. It can be easily observed that the projected amount of China's CO₂ emissions from 2020 to 2050 showed large disparities across the current literature.

Table 2
Research on CO₂ emissions projection of China under two broad categories.

Research category	Major research finding	Reference
Future trajectory of CO ₂ emissions in China	There is an EKC curve for China's CO ₂ emissions in the long term; however, the inflection point is expected to occur after 2020 at a relative high-income level	[107–109,126,127]
	China's CO ₂ emissions will keep increasing before 2020	[114–116]
	The peak of China's carbon emissions may be reached between 2020 and 2035	[111,117–119,121,122]
	China will be able to peak its CO ₂ emissions by approximately 2030	[128–130,131–133,142,143]
Timeline, pathway and cost-benefit to peak China's CO ₂ emissions	China has a large opportunity to reach an earlier peak of its CO ₂ emission between 2020 and 2030	[134–137,144,146–149]
	To peak CO ₂ emission by 2030, China ought to transform towards a sustainable service economy, improve its energy efficiency and demand-side management, enlarge the utilization of CCS and renewable energy resources and continuously introduce new policy instruments and develop stronger policy packages	[153–159,161–164]
	To reach an earlier peak of CO ₂ emissions between 2020 and 2030, China needs to carry out more immediate and deeper transformations in its socioeconomic development and undertake enhanced emissions reduction efforts, including the promotion of new-normal development and new-type urbanization, high penetration of renewable sources in energy mix, effective implementation of newly issued climate directives and INDCs, and the formulation of more stringent emission mitigation goals	[165,167–169,171–174]
	Peaking CO ₂ emissions before 2025 may cause obvious economic losses, while during 2025–2030, it may have more moderate impacts. Advancing a rapid low-carbon development transition, encouraging industrial upgrading and technological innovation, and promoting the renewable-coal replacement can help alleviate economic and welfare losses caused by an earlier peak. Additionally, the potential impacts will vary greatly by sectors, with energy and energy-extensive industrial sectors suffering the most	[161,166,174–178,183]

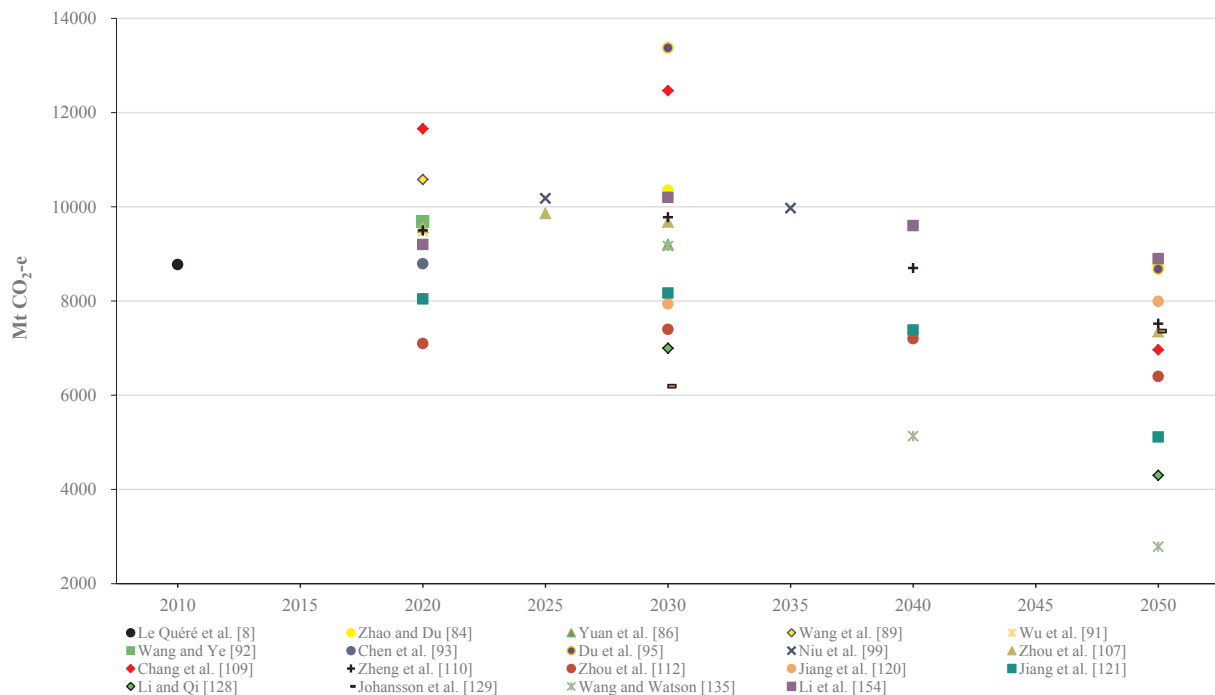


Fig. 3. Projected CO₂ emissions of China in different studies.

The applicability of the EKC hypothesis to China's CO₂ emissions was examined using various time series and panel models. Several studies discovered that there indeed had an inflection point in China's CO₂ emissions *per capita* with rising income levels [107,108]. Such an inflection point was likely to occur around 2030 under China's current economic and income growth situations [109], but it might occur earlier if accelerated technical progress and stricter environment regulations [107], as well as stronger climate mitigation actions [110], were implemented. Moreover, it has been widely recognized that CO₂ emissions increases are jointly determined by emission-driving factors and emission-reduction actions [111]. Hence, a variety of factor analyses and econometric models were used to examine the driving and restraining forces of China's emissions growth and estimate their potential effects in future [112,113]. In the very short term, it was foreseen that following current socioeconomic growth and carbon intensity decline, China's CO₂ emissions would keep increasing until 2020 [114,115]. As for the longer-term trend, China's CO₂ emissions might maintain a steady growth in the coming years but would tend to decline in the long run [116]. A peak of CO₂ emissions might be reached between 2020 and 2035 in China, with total emissions of approximately 10–14 Gt CO₂-e [117,118] and *per capita* emissions of approximately 8.0–9.5 tonnes [119].

Furthermore, some studies adopted a combination of multiple models to forecast CO₂ emissions [120]. Wang et al. [121] and Niu et al. [122], using three types of models, estimated that by converting into a high-quality, middle-speed economic growth, China might cap its CO₂ emissions over 2030–2035 at approximately 11 Gt. Sun and Liu [123] systematically compared two types of methods. They discovered that China's CO₂ emissions, as projected from sectors to the entire country, showed higher accuracy than from direct national-level predictions. Additionally, there showed obvious gaps in the projections between individual models and integrated modelling frameworks [124]. By comparison, the combination of diverse models usually showed the potential to reduce modelling risk and enhance the accuracy of CO₂ emissions projections [125].

In addition, a growing number of studies have attempted to project China's CO₂ emissions from partial or general equilibrium perspectives. System dynamics models were used to analyse the short-run changes in

CO₂ emissions, projecting that China was highly likely to realize its target for carbon intensity reduction but could not prevent the growth of its total CO₂ emissions by 2020 [126,127]. Technical-based studies were also conducted to depict low-carbon technical roadmaps from bottom to top. The main results showed that China had the technical potential to approach a plateau or reach a peak of CO₂ emissions by 2030 [128], but a full realization of such potential would require billions of dollars of investment in the high-energy efficiency and low-carbon technologies [129,130]. In addition, some studies used input-output and CGE models to simulate China's future CO₂ emissions from top to bottom. It was projected that an absolute reduction of CO₂ emissions would be hardly achievable prior to 2020 but that an optimal balanced economic mode should be practised and begun immediately to lower future emissions trajectory [131,132]. Under current energy and carbon intensity reduction efforts, China's CO₂ emissions were expected to peak around 2030 or slightly later [133]. However, the country could achieve an early peak of CO₂ emissions before 2030 if it transformed into a decarbonized industrial and energy structure [134,135], introduced market-based diverse emissions reduction instruments [136], and imposed more ambitious climate pledges [137].

Moreover, the application of bottom-up (BU) and top-down (TD) approaches was compared for China's CO₂ emissions analyses. Both methods had their advantages and disadvantages and often exhibited wide gaps in emissions projections [138,139]. A soft-link of TD and BU modelling into integrated assessment modelling emerged as a pragmatic approach to reduce disparities [140], which has thus been increasingly used to explore CO₂ emissions trends [141]. Several studies based on IAMs projected that if China fully adopted the advanced technologies and followed a low-carbon development pathway, the country would be able to cap its CO₂ emissions at approximately 10–12 Gt by 2030 and then begin to decrease them afterwards [142,143]. Assuming a full deployment of renewable energy resources, China could cap its consumption of high-carbon fuels at the end of 2015–2020; and then, it could peak the energy-related CO₂ emissions before 2030 at approximately 9.5 Gt [144]. Additionally, under the combined effects of energy efficiency improvement, demand-side electrification and energy mix decarbonization, China's CO₂ emissions would be reduced by 3 Gt by 2050 [145].

Some other studies performed more systematic comparative analyses of China's CO₂ emissions projections from different models [133,146,147], research institutions [148] and policy alternatives [149]. By comparison, most studies concurred that the peak of China's CO₂ emissions might appear in the 2020s or around 2030, with the values ranging from 7 to 12 Gt in alternative socioeconomic development scenarios. However, owing to the differences in modelling structure and approach as well as the differences in scenario setup, technical assumption and climate policy implementation, current projections on the specific peaking time and peaking value still showed obvious disparities [150,151]. Moreover, the dynamics of China's CO₂ emissions continued to face a variety of uncertainties, especially those in fundamental driving forces, implying a crucial importance to enhance the uncertainty analysis of projection results [152].

3.2. Timeline, pathway and cost-benefit to peak China's CO₂ emissions

Following the release of an official CO₂ peaking pledge, the literature begins to show increased concerns about the preconditions and measures required to cap China's CO₂ emissions at or even before 2030, as well as the associated costs and benefits.

Regarding the conditions that China's socioeconomic development ought to meet for peaking CO₂ emissions by 2030, the maintenance of a reasonable and green GDP growth, the reduction in energy intensity per unit of GDP, and the decline in carbon intensity of energy were identified as three key links [153]. The transition towards a low-carbon service economy would be integral for China's decoupling of economic growth and CO₂ emissions [154]. To promote this transition, China needed a variety of active efforts on energy efficiency improvement and structure decarbonization [155] as well as on industrial upgrading and intensified climate governance [156]. Additionally, the electric power sector was reported to fulfil a decisive role in decarbonizing the energy system; and in turn, in capping national CO₂ emissions [157]. This sector must largely improve the application of clean coal and CCS technology and the deployment of renewable energy resource [158]; and it must also practise demand-side management [159]. Moreover, several studies evaluated the effects of energy-saving and emission-reduction policies currently implemented or proposed in China. Major results noted that the selection and construction of policy combination had decisive impacts on both the time required to arrive a peak of CO₂ emissions and the level of such a peak [160]. Only the current intensity-based policies were unlikely to stabilize CO₂ emissions by 2030, demonstrating a critical demand for new and stronger policy instruments [161]. A full implementation of carbon pricing, in forms of carbon tax or carbon trading, was also suggested. According to simulation studies, China could reach a peak of CO₂ emissions in 2030 with a carbon price higher than \$25/t CO₂ [162,163]. If further implementing carbon pricing with auction or revenue redistribution, China could not only cap its CO₂ emissions in a cost-effective manner but also coordinate emissions abatements with reductions in poverty and urban-rural gaps [164].

More ambitious studies examined whether China could achieve an earlier peak of its CO₂ emissions and accordingly discussed the enhanced conditions and emissions abatement efforts required. From an energy perspective, it was reported that a rapid and high penetration of renewable energy might cap China's fossil energy use by 2020 and then drive energy-related CO₂ emissions to a peak in 2025 [165]. In this case, the share of non-fossil sources in the energy mix should be increased by more than 20%, while carbon intensity should be decreased by over 65% [166]. Moreover, China has begun a new-normal development stage characterized by structural change and high-quality growth [167]. The International Energy Agency [6] investigated the energy and climate implication of China's transition towards a greener and more services-based economic model. The simulation analyses indicated that a fast development transition of China could make its coal consumption peak before 2020 and decline by almost 15% to 2040 and

meanwhile could markedly reduce the growths in national energy demands and associated CO₂ emissions. It was future reported by [168] that, if the shut-down of excess capacity and the development of the service economy and new-type urbanization made good progress over the next few years, China's CO₂ emissions could reach a peak in 2025 and decrease afterwards. Several of the most updated studies have already shown the effects of recent developmental transitions on China's CO₂ emissions. A structural break in China's CO₂ emissions trajectories was observed around 2015 and largely attributed to changes in industrial and energy structures [169]. If these nascent transitions continued, the structural decline of CO₂ emissions would likely be sustained in China and enable the peak to arrive much earlier. Meanwhile, the pattern of China's CO₂ emission flows also changed significantly in foreign and domestic trade [170]. China's emissions abatement efforts, thus, needed paying more attention to trade shifts and CO₂ emissions embodied in both the rising South-South trade and the domestic interregional trade.

How the recent new-normal development transition will work with newly issued energy and climate policies of China's 13th Five-Year Plan and its INDCs has also been simulated by scholars [171]. With enhanced efforts on energy decarbonization, such as a higher carbon tax and fossil resource tax, China might observe a peak in its coal use around 2020 and then see its CO₂ emissions level off around 2030 at approximately 10 Gt [172]. Implementing enhanced emissions reduction efforts not only in energy but also in broader fields would considerably increase the possibility of China to achieve an earlier peak of CO₂ emissions around 2025 at a lower quantity of the total emissions [173]. Furthermore, a comparative analysis of alternative policy scenarios showed that the peaking point of CO₂ emissions tended to shift forward with more stringent climate mitigation goals and more forceful portfolios of corresponding policies and measures. With a gradually shrinking amount of available allowances and increased carbon prices, China's upcoming national emissions trading scheme (ETS) had the potential to cap nationwide CO₂ emissions by 2025 and to achieve a cumulative reduction of 20 Gt emissions over the 2017–2030 period [174].

Furthermore, the potential impacts on the economy and the society of achieving an earlier peak of CO₂ emissions have attracted growing attention. It was determined that a peak of China's CO₂ emissions was technically achievable by 2025 but at massive economic costs and loading energy system with seriously heavy burdens; in comparison, a peaking point occurring after 2025 might have more moderate impacts on both the economic and energy systems [161,175]. The years 2020–2025 would be a key period for China to realize an earlier and lower peak of CO₂ emissions, during which a rapid transition to a low-carbon economy would contribute to alleviating future emissions reduction costs [166]. Additionally, some studies have conducted more systematic cost-benefit analyses. It had been reported that although pursuing an earlier peak of CO₂ emissions might cause certain economic and welfare losses to China, the ultimate outcome would be very uncertain and highly dependent on both national socioeconomic contexts and the countermeasures adopted to address this issue. The potential negative effects on China's economy and welfare could be largely alleviated by establishing proper targets of economic growth, accelerating technological progress and industrial upgrading, and promoting non-fossil energy deployment [176], but such effects might be exacerbated by the enhanced consumption level and rising urbanization [177].

Moreover, the impacts of reaching an earlier peak were found to vary greatly by sector, with some sectors suffering substantial losses whereas others gaining benefits [174,178]. Given the unavoidable growth trend of transport and household emissions, an early peak implied a much tighter budget of CO₂ emissions for the industrial sectors [179]. As a result, the energy processing, conversion and supply sectors and the energy-extensive industrial sectors were expected to be the most seriously affected [180]. Effecting a rapid decarbonization would

become an exclusive requirement for energy system, requiring immediate and massive financial supports and investments to phase down low-efficiency power generation units and enhance the clean utilization of coal [181], to promote the wide diffusion and application of CCS technologies [182], and to accelerate the large-scale development of renewable energy and smart grids [183,184]. Notably, both the market-based reforms of energy resource prices and the rising carbon prices with tightened CO₂ emissions budgets might impose increasing cost burdens on energy-extensive manufacturing industries and in turn might cause significant changes in industrial competitive patterns [113]. Therefore, the sector-specific subsidy measures should be considered to lessen the potential competitiveness damages, particularly for vulnerable sectors.

4. Research on CO₂ emissions projection of India

India is the second largest developing country and the developing-world's second largest CO₂ emitter. Unlike China, where the growth of emissions has begun to slow down notably over the past five years, India is still experiencing a rapid growth in CO₂ emissions. This country has not committed itself to stopping emissions growth by a specific year but has pledged to reduce carbon intensity by 33–35% by 2030. Given the increasingly large scale of CO₂ emissions and intensity-based emissions reduction commitment, India not only plays an important role in shaping future developing-world emissions but also has a good representative of many other developing countries. Hence, in-depth studies on the dynamics of India's CO₂ emissions will contribute significantly to better grasping future emission trends in the developing world. The section describes the recent relevant literature from two perspectives: estimating the future CO₂ emission trajectories of India in alternative socioeconomic development scenarios and exploring the possible emissions pathways to meet global climate targets, as shown in Table 3.

4.1. Future trajectory of CO₂ emissions in India

The possible trajectory of India's CO₂ emissions, spanning from 2020 to 2100, has been investigated by a variety of studies and displays significant gaps across alternative socioeconomic development and emissions reduction scenarios, as shown in Fig. 4.

Regarding the dynamic relationship between CO₂ emissions and economic growth in India, several studies found the evidence of a short-run causality but failed to identify any long-run equilibrium or causality [185,186], while several other studies discovered the evidence supporting the existence of a long-run positive relationship [108,187]; all

of these studies denied the applicability of the EKC hypothesis to India. It was implied that, for the short term, Indian CO₂ emissions tended to increase with rising income levels, and that reducing emissions might hurt the economy if no action was taken to offset abatement costs. However, there also existed opposing viewpoints that validated the EKC hypothesis for Indian CO₂ emissions. Some studies took structural breaks into consideration, noting that India's CO₂ emissions were highly elastic to rising incomes *per capita* in the short run, but such elasticities tended to decrease over the long run [188]; in addition, national consumption of coal would play a notable role in affecting CO₂-economy interactions [189]. They foresaw that Indian CO₂ emissions might keep increasing in the near future but would be able to attain a peak at high enough income levels and with less reliance on coal use.

Several studies further explored how energy system changes would affect the CO₂-economy interaction. The CO₂ emissions resulting from different types of fossil fuel consumption were all detected as an inverse U-shaped response curve to economic growth in India, but the curve showed large gaps in time to hit the inflection point [190]. Additionally, increasing the share of renewable sources in the energy mix was proved to reduce long-run elasticities [191,192]. It had been detected that renewable energy use would help India arrive the inflection point of its energy-related CO₂ emissions at the earlier time [193]. Moreover, there existed a risk of an N-shaped curve for India. In other words, India's CO₂ emissions would at first increase and then begin to fall at a high-income level; however, a re-increasing trend might appear again with a further economic growth [194]. Overall, current studies have generally concluded the sustained growth in both the *per capita* and the total CO₂ emissions of India in a near future, however, the findings about the long-term dynamics are still controversial and require further scrutiny.

Some studies analysed the changes in CO₂ emissions driving forces and calculated their potential contributions to future emissions growths. India is widely seen as the next developing superpower and as a destination for large-scale manufacturing hubs. A unidirectional Granger causality from industrialization to CO₂ emissions was reported for India, indicating that the rapidly expanding industrial production would greatly raise India's CO₂ emissions in its industrialization process [195]. Additionally, given the staggering gaps in energy and emission efficiency between India and advanced nations, we could foresee that the production shift into India might lead to dangerous increases in CO₂ emissions in both India and globally [196]. Moreover, India is expected to overtake China as the world's most populous country in ten years [197] and usher in an accelerated stage of urbanization [198]. It had been reported that declining population and ageing tended to abate CO₂

Table 3
Research on CO₂ emissions projection of India under two broad categories.

Research category	Major research finding	Reference
Future trajectory of CO ₂ emissions in India	Both the per-capita CO ₂ emissions and the total CO ₂ emissions of India will show sustained growths with rising income levels in a near future India's CO ₂ emissions are very likely to maintain a growing trend until 2030, behind which the rapidly expanding industrial production, increased population and urbanization, and booming energy demand are major driving forces India's CO ₂ emissions are expected to continue to increase until 2050 under current development trends and climate mitigation actions	[108,185–189] [194–196,198–200,204,210–212] [217–220]
India's CO ₂ emissions under the INDCs and 2 °C target	Even if all the pledged targets and plans are successfully implemented, India's INDCs recently submitted to the Paris Conference still cannot prevent Indian CO ₂ emissions from growing by 2030 If an emissions budget constraint based upon the global 2 °C target and the international burden-sharing schemes is imposed, there is a chance that India may reach a peak of its CO ₂ emission between 2025 and 2040. However, the associated economic costs will be too heavy for India to pay To make it feasible to peak CO ₂ emissions before 2040, India must undertake more aggressive climate mitigation actions in various fields of its socioeconomic development, such as a wide application of clean coal and CCS in coal-based large point sources, replacement of coal by renewable energy sources, improvement in electrification and energy efficiency across end-use sectors, as well as a wide range of sustainable efforts in the transport and consumption fields. Moreover, technical and financial assistances from the international society are urgently needed	[62,223] [76,224–229] [226,231–235,237,238,241–243]

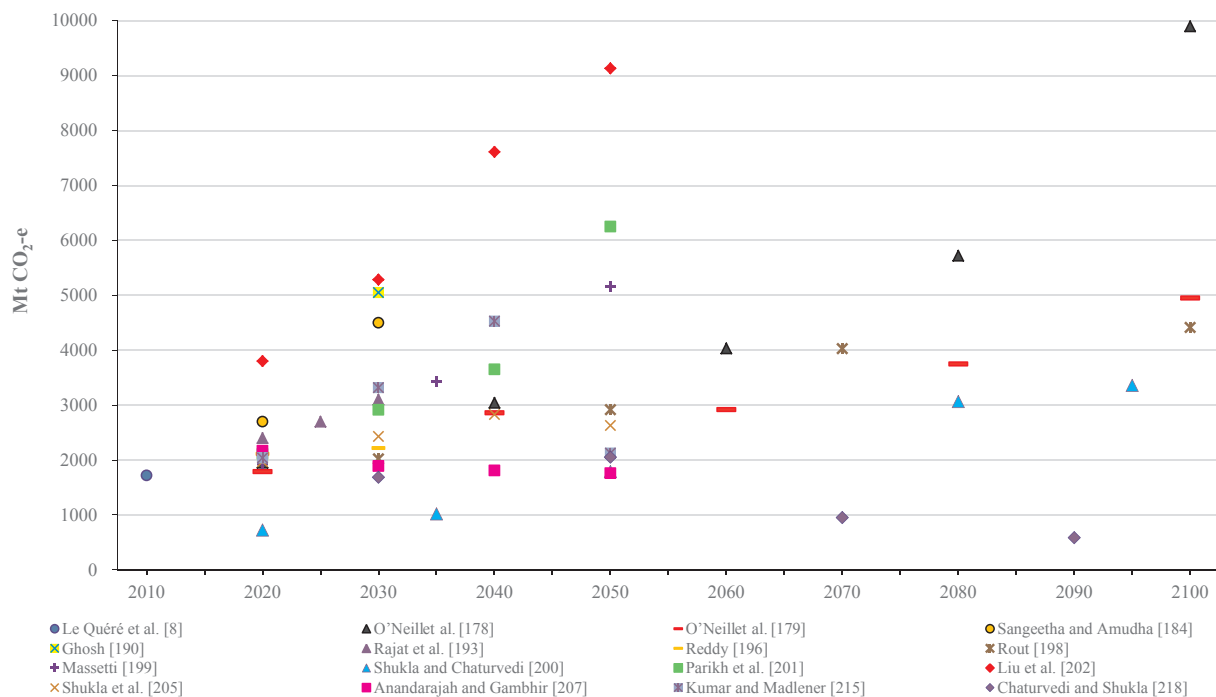


Fig. 4. Projected CO₂ emissions of India in different studies.

emissions but increasing population and urbanization tended to raise them. The projected growth in India's CO₂ emissions presented a wide range across alternative demographic scenarios, implying population control policies [199] and sustainable urbanization [200] might generate climate benefits. Moreover, several studies noticed that urbanization had positive but less than proportional effects on energy consumption and CO₂ emissions in India [201], and several studies further discovered that urbanization effects would be stronger on household sectors [202,203]. Thus, India's CO₂ emissions were widely predicted to continue to increase for the next several decades under a plausible range of urbanization paths.

Moreover, given the ongoing industrialization and urbanization, and considering the present serious electricity shortage, India's electricity demand would experience a booming growth and drive national CO₂ emissions to keep growing until 2030 [204]. It was thus imperative to fuel India's future demands via energy efficiency improvements and clean energy resources. Additionally, the roles of globalization and financial development in India's CO₂ emission growth were also examined. It was noted that without a sound institutional and governance framework, rising financial liberalizations might be harmful to India's CO₂ emissions situation [205,206]. Besides, the current pattern of international trade made India a net carbon exporter and hence deteriorated its domestic emissions reductions [207]. However, it was also argued that if the country chose more reasonable development patterns and strengthened governances, both financial development [208] and participation in globalization [209] could translate into raising India's economy and simultaneously help reduce CO₂ emissions over the long run. Thus, it had great significance for India to encourage climate-friendly international trade and low-carbon finance.

Furthermore, a variety of bottom-up, top-down and integrated assessment models were used to simulate India's CO₂ emissions under alternative development scenarios. Several studies explored the optimized pathways to meet India's increasing energy demands and the associated CO₂ emissions profiles. It was generally concluded that the energy-related CO₂ emissions would show continuous increases in India until 2030, behind which the expanding thermal power capacity and its coal-dominant structure would constitute the major drivers [210]. However, owing to different assumptions of economic growth, energy

efficiency, energy mix and CCS application, the projected growth of CO₂ emissions showed large disparities across studies, with total emissions varying from 3.5 to 6.0 Gt in 2030 [211,212]. According to comparative analyses of different scenarios, India had large potentials to achieve 20%–35% reductions of CO₂ emissions relative to Business-as-Usual (BAU) cases by increasing energy efficiency and accelerating renewable energy deployment [213]. If further combining renewable energy development with electrification and rural building, India could achieve greater reductions of CO₂ emissions by 2030 but doing so would require billions of dollars of investment [214]. Additionally, some studies modelled CO₂ emissions while taking into consideration a broader range of socioeconomic changes. If India widely improved sustainable conditions and transformed itself into a green economy, this country could attain much more substantial reductions in its primary energy consumption and CO₂ emissions by 2030 and improve living quality at the same time [215]. Additionally, it was aware that the production-based CO₂ emissions and net-exported emissions in India presented very significant increases since 2010 and the intermediate manufacturing products constituted the major contributors. As India had been poised to succeed China as the next world manufactory, international cooperation to optimize the trade structure and domestic effort to reduce coal consumption and improve energy efficiency would play important roles in mitigating Indian future CO₂ emissions [216].

In addition, a number of studies attempted to make the longer-term projection of India's CO₂ emissions. Considering the present extremely low *per capita* energy use and the potentially massive population and economic growths, India's energy demand was projected to experience a substantial increase by 2040 and make the largest contribution to almost 30% of global demand growths [6]. Although the share of coal in the energy mix could be largely reduced and in turn alleviate emissions growths, to satisfy such a swiftly growing energy demand would keep driving up Indian CO₂ to 2040 and 2050 [217]. Implementing a low-carbon electricity target could reduce India's CO₂ emissions by 4–6% but would still be incapable of enabling them to peak [218]. To further combine the low-carbon electricity target with a carbon tax would largely enhance the penetration of renewable sources in long-term energy mix, but a tax above \$10/t CO₂-e would be excessively costly for India to implement in recent decades [219]. Moreover, how

India could align its socioeconomic development visions with climate change mitigations was also examined. Major results showed that implementing the national schemes of sustainability vision and low-carbon development could cut India's CO₂ emissions by nearly 70% by 2060 [220] while also promoting inclusive growths and achieving human development targets [221].

4.2. India's CO₂ emissions under the INDCs and 2 °C target

It has been generally concluded that under the current development situation and climate mitigation measures, India is very unlikely to stop the growing trend of its CO₂ emissions before 2050. A long-term sustained growth of CO₂ emissions in India will be an extreme threat to achieve the global 2 °C target. Therefore, India requires more aggressive climate efforts and more fundamental socioeconomic revolutions to control its CO₂ emissions.

India's INDCs, submitted to the COP21, have outlined its latest ambitions on combating climate change. Some studies reviewed India's INDCs and estimated its impacts on future CO₂ emissions. It was reported that none of the recently conceived energy mixes could help India meet its 2030 CO₂ emissions budgets derived from the global 2 °C target and the Greenhouse Development Rights framework [222]. Even with all the newly pledged targets and plans being successfully implemented, INDCs could still not prevent India's CO₂ emissions from increasing by 2050 [62,223]. Thus, it was necessary to set more ambitious targets for emission intensity and non-fossil energy.

In addition to these, some studies assumed that India could meet its CO₂ emissions budgets derived from global climate targets and then explored the optimal development pathways and the associated CO₂ emissions trajectories and emissions reduction costs. Using the principle of equal cumulative emissions *per capita* to set emissions budgets, it was projected that India's annual CO₂ emissions could reach a peak before 2040 at a level below 3 Gt [224,225]. Using the principle of the long-run convergence of *per capita* emissions to set budgets, several studies modelled India's CO₂ emissions under alternative low-carbon scenarios. The results indicated that India could peak its CO₂ emissions at 2.4–3.0 Gt between 2025 and 2030 if it followed renewable-energy and low-carbon economic growth pathways [226]. Moreover, some studies assumed the existence of a globally unified carbon pricing across all regions of the world to limit global average warming below 2 °C. If faced with globally unified carbon taxes, it was forecasted that India could reach a peak of CO₂ emissions, but the specific peaking time might fluctuate from 2025 to 2040 across different technology conditions and emissions reduction pathways [227], or across different economic and industrial growth patterns [228]. Participating in international carbon markets could help India reach the peak of CO₂ emissions more easily, as it could sell allowances to partially offset its emissions abatement costs [76,229].

Generally, the above studies disclosed the existence of an opportunity for India's CO₂ emissions to meet global climate-target constraints. However, to make this happen, India must promote aggressive revolutions in a wide range of socioeconomic fields and doing this might induce overly heavy economic losses [229,230]. First, energy system decarbonization played a key role in meeting India's CO₂ emission constraints. Coal was expected to remain a base source for India's power generation in the next several decades [211]. The extensive application of clean coal technology [231] and large-scale equipment of CCS technology in coal-based large point sources [232] would thus be essential for India to limit its coal-related emissions. In addition, displacing coal by more clean energy and renewable energy had greater potentials in cutting emissions [6]. It was reported that a full exploitation of renewable energy potentials could make India's CO₂ emissions peak at approximately 2035–2040 and could achieve more than 70% of emissions reductions by 2050 [233,234]. To realize the potentials, India must not only formulate more visionary renewable energy plans and provide stronger policy supports and research &

development incentives [226], but also obtain technical and, particularly, financial assistances from the international community [235].

Second, improvements in energy efficiency across broad end-use sectors would play an important role in attaining ambitious mitigation targets. Scenario simulations projected that final energy demand and CO₂ emissions in India would be significantly decreased by energy efficiency improvements, and the effects would be particularly prominent in the building and transport sectors [236]. More specifically, it was reported that in household sectors, accelerating the adoption of high energy efficient appliances could reduce India's household electricity consumption by 10–27% by 2030, with a corresponding reduction in household CO₂ emissions by 30% [237]. In the transport sector, an extensive promotion of energy efficient vehicle configurations could greatly cut down India's transport CO₂ emissions by 20–40% [238]. Moreover, if the energy efficiency and renewable energy measures were well combined, India could attain an earlier peak of CO₂ emissions and achieve a greater abatement of cumulative emissions by 2050 [239]. Finally, compared with low-carbon pathways relying solely on energy systems or carbon pricing, sustainability movements at global and national levels could help realize the same levels of CO₂ emissions mitigations at substantially lower costs and welfare losses [240]. Therefore, India should carry out a broad range of sustainable efforts to cost-effectively deepen its decarbonization and meet emissions budgets [241]. As the transport sector continued to grow very rapidly and depended heavily on oils, sustainable transport strategies and actions would be particularly important for India, which could reduce CO₂ emissions and simultaneously improve energy security and air quality [242]. If India pursued to attain a more ambitious climate target, such as a 1.5 °C temperature stabilization, this country must undertake immediate and diverse actions in terms of sustainable transport transformations involving not only green infrastructure and policy innovation but also sustainable human behaviour [243].

5. Current research consensus and policy implication

Through a critical review of the up-to-date literature, this section summarizes the current study consensus regarding the peak of CO₂ emissions in the developing world and in the top two developing emitters (China and India), and discusses their important policy implications for broad developing countries to cap their CO₂ emissions as early as possible.

5.1. Peak of CO₂ emissions in the developing world

CO₂ emissions of the developing world are widely expected to keep increasing for decades and contribute predominantly to future global emissions growths. Expanding economic activity and ongoing urbanization are two fundamental forces that drive up future CO₂ emissions [22–25]. A growing international trade also contributes to raising CO₂ emissions, particularly in the near future [28–30,46]. What is worse, production outsourcing and the related carbon leakage from developed to low-wage developing countries may not only cause extra increases in CO₂ emissions in the developing world but also pose net effects on raising global emissions [45,49,56,57]. For the long-term dynamics, there is evidence to show that CO₂ emissions in many developing countries will first increase and then begin to decrease when reaching a considerably high-income level [17–19]. However, the time and the conditions of arriving at that inflection point vary greatly across countries with different characteristics and at different stages of development [20,21,27]. Therefore, it remains difficult to determine a CO₂ emissions peak for the entire developing world.

However, to limit the global warming below 2 °C, it is indispensable to stop CO₂ emissions increases in the developing world. The INDCs submitted by developing countries to the Paris Agreements outline their latest targets and plans to combat climate change. It is generally concluded that these INDCs can enable substantially enhanced emissions

reductions in developing countries compared to current policy scenarios. However, even if all of these INDCs are fully actualized, they remain unable to stop CO₂ emission growth in the developing world by 2030 [62–65]. Thus, several critical prerequisites are highlighted for the developing world to mitigate CO₂ emissions much more substantially, including the establishment of clean and renewable energy systems for feeding swiftly increasing energy demands [75,77,80–82], the energy efficiency improvements across end-use sectors for suppressing energy demands [88,90–92], the implementation of a sustainability-oriented industrialization and urbanization process and the promotion of low-carbon lifestyles for decoupling socioeconomic growth and CO₂ emissions [43,100–102,105].

5.2. Peak of CO₂ emissions in China

By analysing the possible changes in the major driving factors of CO₂ emissions and estimating the potential effects of existing emission mitigation actions, China's CO₂ emissions are expected to continue growing until 2020. In other words, China's CO₂ emissions are unlikely to peak in the short term [115,126,127,161]. However, it is widely recognized that China's CO₂ emissions tend to evolve a trend that first increases and then decreases over the long term, implying the existence of a peak point of annual emissions [107,108,116]. Although different viewpoints have been proposed, a lot of studies postulate that China is most likely to cap its CO₂ emissions during the period of 2020–2035 [111,119,121,122,133,136,137]. Within this range, identifying the specific time and level to peak CO₂ emissions remains challenging due to diverse uncertainties in future socioeconomic developments and implementation schedules of climate policy packages.

Regarding China's commitment in the 2015 INDCs, researchers generally agree that China can indeed reach a peak of CO₂ emissions by 2030. Maintaining a reasonable rate of economic growth, reducing the energy intensity of GDP and cutting the carbon intensity of energy are three general premises for capping CO₂ emissions [153,160]. If these premises are satisfied, the commitment to peak CO₂ emissions by 2030 may well be attained at a total value ranging between 9Gt and 12Gt [118,148,152]. Moreover, given the national transition to a new-normal development and the recent initiation of more ambitious climate plans, China also has a large opportunity to achieve an earlier peak of CO₂ emissions between 2020 and 2030. To seize this opportunity, the country should not only optimally utilize the extant emissions reductions instruments, but also introduce newly enhanced policies and measures targeted at technical and efficiency improvements, decarbonization of key emission sources [165], transformation towards a green service economy and low-carbon lifestyle [167–169], and

implementation of nationwide carbon pricing [171–173]. Additionally, China requires establishing a proper low-carbon sustainable development pathway as quickly as possible, which can help alleviate carbon lock-in effects and assist in achieving an earlier and smaller CO₂ peak by more cost-efficient means [166,176,177].

5.3. Peak of CO₂ emissions in India

Given the current extremely low CO₂ emissions *per capita* and the forthcoming accelerated socioeconomic development, it is widely recognized that India will develop a rapidly growing trend of CO₂ emissions in the near future [108,185–187,194] and that the country cannot terminate this trend by 2030 [210–212] or even by 2050 [217–220]. India is expected to become the next developing superpower of the world and the next most populous country [197,198]. The rapidly expanding industrial production, uncontrolled population growth and accelerated industrialization process will result in a sustained growth of India's national CO₂ emissions [195,196,199–201]. Additionally, to address the serious power shortage, India's electric power generation will witness a booming growth and constitute a major driver of CO₂ emissions growth [189,204]. Moreover, a variety of energy and climate actions have been currently implemented in India or newly proposed by India's INDCs, which are expected to significantly slow down national CO₂ emissions growths. However, even taking these emissions reduction potentials into account, India remains incapable of capping its CO₂ emissions by 2050 [62,213–216,222,223].

The sustained growth of CO₂ emissions may make India overtake China as the largest contributor to global future emissions growth, which is extremely dangerous for achieving global climate targets. However, there is also a possibility for India to meet its CO₂ emission budgets derived from a global 2 °C target. Under this scenario, India can attain its CO₂ emissions peak before 2040 at a value below 3 Gt, and the specific peaking time may range from 2025 to 2040 in alternative socioeconomic development and emission reduction pathways [224–228]. To actualize this possibility, India must take far more aggressive mitigation efforts and fundamental socioeconomic revolutions [229,230]. The top four priorities include (1) a significant improvement in energy efficiency across broad end-use sectors [236–238], (2) a wide application of clean coal and CCS in coal-fired large point sources [231,232], (3) a large displacement of fossil fuels by renewable sources in the energy mix [233,234], and (4) a rational planning of urbanization and sustainability-oriented behavioural changes in various fields of the economy and society [240–243]. Moreover, it is also widely expected that no matter by what means, India has to pay a huge amount of emissions reduction costs for meeting its CO₂ emission budgets

Table 4

Classification of current study methodologies and their analysis frameworks.

Broad category	Specific method or model	Analysis framework
Econometric methodology	EKC, decoupling analysis, etc.	Detect the dynamic relationships of CO ₂ emissions and economic growth, and then, test whether there is an inflection point of emissions growth
	Factor decomposition analysis, LMDI model, Kaya identity, STIRPAT model, etc.	Decompose changes in CO ₂ emissions into changes in several related factors, and then, make projections of future emissions based on decomposition analysis and trend analysis of these related factors
	Time series model, panel model, grey model, etc.	Determine the relationships between CO ₂ emissions and major emission driving forces, and then, examine possible changes in major driving forces and their effects on future emission growths
	Diverse combination of econometric methods and models	Employ different types of methods/models to predict future CO ₂ emissions with an aim of reducing modelling risk and enhancing the projection accuracy
Partial or general equilibrium simulation methodology	Diverse energy planning models, system dynamics, MAC, etc.	Perform a bottom-up simulation of energy and CO ₂ emissions systems from a partial equilibrium analytic perspective
	Diverse input-output and CGE models	Perform a top-down modelling of the national economic system and its related CO ₂ emissions from a general equilibrium perspective, and consider various sectors and agents as well as their interactions
	Diverse IAM models	Soft-link bottom-up and top-down modelling into integrated assessment modelling, and comprehensively assess the potential impacts of driving forces and emissions mitigation actions and their feedbacks on the economy and climate

[230]. The country, by itself, cannot afford such overly heavy economic burdens and hence sorely requires large-scale financial assistance from the international community [218,222,244].

6. Future research prospects

While some findings have been reported in the current literature, when and how to reach a peak of CO₂ emissions in the developing world is still not clearly answered. To offer better answers, the following four topics urgently require further study.

6.1. Improvement in study methodology and data

A variety of methods and models have been employed to forecast CO₂ emissions from developing countries over the past decade. These can be generally classified into two broad categories: the first category is the econometric methodology, including various forms of EKC, Kaya identity, time series, panel and grey models; the second category is the partial or general equilibrium simulation methodology, including various types of energy planning, marginal abatement cost (MAC), system dynamics, input-output, CGE and IAM models. The classification of the current study methodologies and their analysis frameworks are presented in Table 4.

As observed in the recent literature, there remain large disparities in CO₂ emissions projections across alternative methods and models. Hence, improvement and perfection of the study methodology remain a critical theoretical and practical issue to be resolved. Regarding the econometric methodology, since any individual models have their own advantages and disadvantages, future studies should perform more frequent combined applications of diverse econometric models to reduce modelling biases [124,125]. Additionally, it is also proposed that econometric models be integrated with advanced intelligent computation techniques to enhance prediction accuracy, such as particle swarm optimization and artificial neural network [17,204].

Relative to the econometric methodology, partial or general equilibrium modelling methodology serves as a powerful instrument for generating more realistic projections and exploring the possible pathways to attain CO₂ emissions peaks. Based upon the progress of recent studies, we suggest making potential improvements in simulation-based methodology from four aspects. First, despite having greatly evolved in the past decade, energy planning models still cannot adequately reflect the unique features of developing countries, such as socioeconomic nuances, low electricity accessibility and energy-water conflict [40–42]. Hence, additional efforts are needed to develop more contextual energy planning models for developing countries. Second, IAMs are usually built on macroeconomic theories and rarely consider the behaviours of micro subjects. Thus, introducing a module of micro agent-based modelling and integrating it with macro IAMs is a significant direction for capturing the micro-to-macro evolution process and in turn building more inclusive simulation tools. Third, various simulation studies often show significantly inconsistent results, and this has troubled policymakers. Thus, more inter-comparison model studies are warranted for the future literature.

Fourth, the high and complex uncertainties in socioeconomic development pose a great challenge to CO₂ emissions projections of developing countries [94,152]. The current literature usually employs diverse scenario settings to address this issue, which only considers certain possible futures but cannot account for stochastic uncertainties. Two strands of research are recommended for addressing this limitation. On the one hand, additional efforts are needed to identify the major sources of uncertainty in CO₂ emissions projections for a developing-world context, particularly the uncertainties in fundamental driving forces of emissions. Meanwhile, advanced artificial intelligence techniques, such as Monte Carlo and Multi-Agent, should be increasingly incorporated into uncertainty simulations, which can improve the capability of models to represent stochastic uncertainties. On the other

hand, future research requires constructing the scientifically standardized risk assessment procedures that can systematically examine uncertainties across modelling input, parameter, structure and output, and develop the guidelines for making climate decisions based on uncertain modelling results, both of which will help offer policymakers more robust recommendations.

In addition to the study methodology, a continuous improvement of study data is equally important. Because of the weak statistical foundation and the early reluctance to make data disclosures, carbon emissions studies on the developing world have been seriously troubled by issues of missing data, inferior data quality and data unavailability [42,245]. Against this, this study proposes making a continuous improvement of study data through the following efforts. First, the Paris Agreements have introduced a mechanism of periodic emissions stocktaking, which asked each of the parties to submit emissions inventories and necessary emissions reduction information every five years since 2023. Future studies need to determine how we can utilize the existing energy, industrial, agricultural and land statistical systems of developing countries to establish their regular statistical system on carbon emissions, which may facilitate emissions stocktaking and replenish missing data. Second, additional efforts deserve to be put into improving data quality, particularly the explicit definition and unification of statistical indicators and standards; professional capacity training; as well as development of data collection, calculation and bias correction techniques suitable for developing countries. Lastly, to enhance the availability of study data, future work not only needs launching open climate data websites in developing countries but also should explore how to reconcile developing-world data with models usually built by developed countries.

6.2. Key country groups and fields to peak CO₂ emissions

Except for a few large emitters, such as China and India, controlling and abating CO₂ emissions is not always on the agenda in most developing countries. When and how to peak CO₂ emissions and then decrease emissions remains a puzzle for most developing countries and the entire developing world. Against this, the literature needs to carry out profound studies under the following two aspects.

The changing trend of CO₂ emissions varies significantly across different groups of developing countries [21,23,27]. Identifying the key country groups for future emissions increases and formulating specific emissions reduction measures are, thus, of vital importance for capping CO₂ emissions in the developing world. The groups of newly emerging economies and populous developing countries are expected to become the two main sources of future global emissions growth. On the one hand, future studies should pay more attention to estimate CO₂ emission tendencies in the major emerging economies, such as the Post-China 16 countries and the Next-11 countries. The shifts in global production chains and the rising trades between developing countries have important implications for CO₂ emissions in the developing world. Although several of the most updated studies have made initial forays into this question [54,55], how these nascent changes will affect the overall pattern of future CO₂ emissions in the developing world, as well as its distribution structure across various developing countries, remains highly unclear and awaits in-depth investigations. For instance, an increasing transfer of CO₂ emissions from China and India to the more underdeveloped countries, e.g., Bangladesh and Sub-Saharan Africa, emerges with global trade shifts. How such a transfer will affect CO₂ emissions and environment-economy trade-offs through direct and indirect mechanisms in the global South, and how to avoid undesirable impacts on overall mitigation efforts of the developing world are important topics for further study. Additionally, Indonesia, Mexico and Turkey rank in the world's top 15 largest CO₂ emitters and show rapid rates of their annual emissions growth; however, little information is available about their emissions projections. The timeline and conditions to cap CO₂ emissions in these countries deserves more attention.

On the other hand, CO₂ emissions increases from populous developing countries require further investigation, particularly in those countries experiencing rapidly rising income levels. It is reported that the rising incomes *per capita* and the resultant growing consumption demands have greatly increased CO₂ emissions in developing countries [46]. Even though technological progress can help mitigate emissions, the demands for basic goods and for a better quality of life from a growing population will drive up CO₂ emissions in developing countries. This evidence implies that countries with rapid population growth and income increase may make increasing contributions to CO₂ emission growth in the developing world. For instance, Pakistan, Nigeria and Bangladesh are the three typical populous developing countries that have a large size and rapidly growing population but show a very low level of *per capita* incomes and CO₂ emissions. Thus, we suggest determining the potential growth of CO₂ emissions with demographic evolution and rising incomes in this country group and, exploring the feasible development pathways that can decouple economic growth and poverty reduction from CO₂ emissions.

Moreover, it has been widely recognized that power generation, energy-extensive industry and city are the three key fields that determine future CO₂ emissions from the developing world [43,78,81]. However, how to implement the low-carbon sustainable development of these fields in various types of developing nations and gain sufficient financial support requires more detailed discussion. First, the mode and the priority of renewable energy development should be examined on a case-by-case basis for developing countries, taking full account of national resource endowments, expected load demands, and the possible conflicts between energy and water or other resources. Second, significant CO₂ leakages have been observed with the production outsourcing from developed regions to emerging economies. It is a pressing task to introduce a new international trade scheme that can largely avoid carbon leakages caused by national differences in emission standards. Third, how to promote climate-resilient urbanization and infrastructure building in developing countries requires further research, as this has great significance to avoid carbon lock-in effects and to deepen post-2030 emissions mitigations. Lastly, the lack of finance and investment is a critical bottleneck for CO₂ emissions reductions in the developing world. Against this, it is urgent that future study to explore the dual-cultivation of domestic green financial systems inside developing countries and more multi-level climate financing channels internationally.

6.3. Peak morphology and post-peak CO₂ emissions in China

The current literature has generally concluded that China can reach a peak of CO₂ emissions by or even before 2030. Beyond this, the morphology of China's emissions peak and the evolution of CO₂ emissions after the peak also play key roles in realizing the global 2 °C climate stabilization target; however, this topic has only been examined in few studies [134,167].

In view of this, the future study should examine the detailed dynamics of China's CO₂ emissions around the peak, with an aim to clarify whether national CO₂ emissions will reach a flat peak (increase to the peak and then immerse in a plateau) or reach a sharp peak (increase to the peak and then quickly decrease). As a long plateau of CO₂ emissions in China will largely increase the difficulty to realize global climate targets, researches should further identify the factors that may lead to a flat peak and formulate the corresponding countermeasures to alleviate this risk. It has been reported that, with aggressive efforts on renewable-based power generation, China's coal consumption and its related CO₂ emissions are likely to peak at around 2020 [165,172]. By contrast, the consumption of oil fuels continues to increase quickly with an ever-increasing demand of transport services; and consequently, transport related CO₂ emissions are becoming one of the most important contributors to the post-2020 emissions growths in China. In view of this, how to effectively depress the growth of CO₂ emissions from the

transport sector by an integrated application of fuel economy improvement, advanced vehicle, alternative clean fuel, spatial transport planning, mass transit and low-carbon transition of travel behaviour deserves further discussions.

Moreover, it is the amount of cumulative CO₂ emissions that determines the global average warming in the late 21st century and beyond. The selection of CO₂ emissions pathways should be converted from reaching an early emissions peak or minimizing emissions at a specific time towards minimizing the cumulative emissions throughout an entire period. Hence, on the one hand, the performance assessment of CO₂ emissions reduction schemes for China should be extended from a long-run point of view, with a particular focus on the lock-in and path-dependence effects. As an illustration, urban infrastructure systems have substantial impacts on not only urban future CO₂ emissions but also urban vulnerability to climate change related impacts, the planning of which must be placed at long timescales of decades or a century. On the other hand, the future study that search for possible pathways to cap emissions needs seriously accounting for the targets of lowering long-term cumulative CO₂ emissions and of mitigating ultimate climatic impacts, rather than traditionally used targets in forms of the minimum annual emissions or the earliest time of peak-reaching.

Furthermore, the realization of global climate targets has been reported to require much deeper CO₂ emissions reductions in the developing world, particularly in China [75,171]. A pressing task is to determine the extent to which China's CO₂ emissions must be reduced under different international burden-sharing schemes and then assess the associated costs and benefits, which can guide China to elaborate more ambitious emissions reduction plans. Meanwhile, the recent shift in global production chains has led to increasing transfers of CO₂ emissions from China to the global South. Such transfers tend to decrease CO₂ emissions in China but increase emissions in its partner countries [54,55]. Additional efforts are thus required to examine the growth and peak of China's CO₂ emissions based on a carbon footprint account, and to evaluate the impact of China's domestic emissions reduction on CO₂ emissions of the global South and the entire developing world.

6.4. Timeline and pathway to peak CO₂ emissions in India

The current literature indicates that India's CO₂ emissions will continue to grow significantly until 2050 under its current emissions reduction actions and plans, and this growing trend poses a serious threat to achieve the global 2 °C target. On the other hand, meeting emissions budgets derived from global climate stabilization targets can enable India to peak CO₂ emissions; however, it will be too costly to be implemented [226,244]. Given the large gap, the scientific community needs paying additional efforts to determine the timeline and operable pathways for India to peak its CO₂ emissions.

First, the setting of future socioeconomic development scenarios directly affects CO₂ emissions projection. Sustainability-oriented transitions in various fields of India's economy and society, particularly in terms of demographic evolution, industrial growth, urbanization progress, income level and consumption pattern, should be incorporated into future scenario remodelling. Second, it is suggested, from bottom to top, carrying out a systematic survey and investigation concerning the availability, applicability and technological and economic properties of diverse emissions reduction measures in India. On this basis, a marginal abatement cost curve can be constructed to present the costs and the potentials of India's CO₂ emissions mitigations at different timescales as well as the corresponding technical roadmaps.

Third, India should conduct a systematic comparative analysis between its current emissions reduction plans and the emissions budgets required to meet global climate targets. On one side, the potential effects of CO₂ emissions reduction plans and policies currently implemented by India's government need being compared with the committed targets in India's INDCs. On the other side, the targets

committed by INDCs need being compared with the emissions budgets and reduction requirements derived from global climate targets and international burden-sharing schemes. After identifying gaps in the two sides, the future study needs formulating enhanced emissions reduction plans and new policies for ensuring an achievement of INDCs' targets; and next, putting forward a set of technically and economically feasible and sector-specific targets to gradually enhance future INDC's targets. Dong this work may provide some operable pathways for peaking India's CO₂ emissions in a bottom-up way.

Finally, abatements of CO₂ emissions in several key fields require further research, particularly in terms of power generation, urbanization and electrification. India has an energy resource endowment dominated by coal and faces a serious electricity shortage. Hence, we propose making more profound studies regarding how to satisfy the swiftly increasing demand of electricity in India by minimum growths in coal consumption and coal-related CO₂ emissions, and accordingly to determine the peak of CO₂ emissions in India's coal sector. Additionally, India has been experiencing an unprecedentedly rapid — but not well-managed—urbanization, causing severe deficits of urban infrastructure and energy service as well as unregulated increases of urban slums and census towns [198,246]. According to the current literature, a growing urban population and a rising urbanization level tend to drive up CO₂ emissions in developing countries [24,25]. India is expected to enter an accelerated stage of urbanization during the next decade. Against this background, the future study needs exploring how to make a decoupling of India's urbanization and CO₂ emissions and how to extensively promote green urban infrastructure construction. Moreover, electrification is another important trend in India. How increasing electrification will influence India's future electricity demand, energy consumption structure and CO₂ emissions and how to combine electrification with electric decarbonization deserves further exploration.

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